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**THE OHIO STATE UNIVERSITY  
RESEARCH FOUNDATION**

FORMATION, STABILITY AND CRYSTAL STRUCTURE  
OF THE SOLID ALUMINUM SUBOXIDES:  
 $\text{Al}_2\text{O}$  AND  $\text{AlO}$

by

Michael Hoch and Herrick L. Johnston

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Cryogenic Laboratory  
Department of Chemistry  
The Ohio State University  
Columbus 10, Ohio

## FOREWORD

This work was carried out at The Ohio State University Cryogenic Laboratory under contract with U.S. Navy, Office of Naval Research Contract Number M6ori-17, Task Order IV, ONR Project Number NR 358 039, with The Ohio State University Research Foundation. This report covers information obtained during the study entitled: "Formation, Stability and Crystal Structure of the Solid Aluminum Suboxides:  $\text{Al}_2\text{O}$  and  $\text{AlO}$ ." It represents the 10th Technical Report of this series.

Director - H. L. Johnston

Editor - E. R. Fultz

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# ABSTRACT

The study of the reactions (1)  $4\text{Al}_{(l)} + \text{Al}_2\text{O}_{3(s)} \longrightarrow 3\text{Al}_2\text{O}_{(s)}$  and (2)  $\text{Al}_{(l)} + \text{Al}_2\text{O}_{3(s)} \longrightarrow 3\text{AlO}_{(s)}$  between  $1000^\circ$  and  $2000^\circ\text{C}$ , by means of a high temperature x-ray technique, indicated the formation of solid  $\text{Al}_2\text{O}$  and  $\text{AlO}$  above certain temperatures.

At  $1000^\circ\text{C}$  no reaction occurs. Between  $1100^\circ$  and  $1500^\circ\text{C}$ ,  $\text{Al}_2\text{O}_{(s)}$  is formed according to reaction (1). Between  $1500^\circ$  and  $1600^\circ\text{C}$ , both reactions, (1) and (2), occur simultaneously, whereas above  $1600^\circ\text{C}$  the latter reaction occurs. On cooling or rapid quenching both compounds disproportionate into  $\text{Al}$  and  $\text{Al}_2\text{O}_3$ .

From the x-ray diffraction patterns the crystal structure and lattice constants of  $\text{Al}_2\text{O}$  and  $\text{AlO}$  were determined. Both are cubic, the lattice constants being 4.98 Å. for  $\text{Al}_2\text{O}$  at  $1110^\circ\text{C}$ , and 5.67 Å for  $\text{AlO}$  at  $1700^\circ\text{C}$ .

## INTRODUCTION

The existence of gaseous AlO has been known from spectroscopic investigations.<sup>1</sup> From their investigation on the gaseous species of the Al-Al<sub>2</sub>O<sub>3</sub> system, Brewer and Searcy<sup>2</sup> concluded that two suboxides of aluminum must exist in the gas phase; these they identified as Al<sub>2</sub>O and AlO. A phase diagram study of Al-Al<sub>2</sub>O<sub>3</sub>, made by Baur and Brunner<sup>3</sup>, revealed the presence of a compound, Al<sub>8</sub>O<sub>9</sub>, melting at 2323° C with a eutectic between Al<sub>8</sub>O<sub>9</sub> and Al<sub>2</sub>O<sub>3</sub>. Beletskii and Rapoport<sup>4</sup> reported the formation of hexagonal Al<sub>2</sub>O by heating Al and Al<sub>2</sub>O<sub>3</sub> in vacuum in the presence of SiO<sub>2</sub> and C and condensing the volatile products.

In the present investigation the formation, in the solid state, of the lower oxides of aluminum, which are not stable at room temperature, was studied by taking x-ray diffraction patterns at high temperatures. The presence of a new compound is shown by the appearance of a new set of diffraction lines. By varying the temperature, the stability of the compound with respect to disproportionation into Al and Al<sub>2</sub>O<sub>3</sub> can be determined. From the position of the diffraction patterns, lattice constants and crystal structure can be determined, and from the relative intensity of the pattern the approximate composition of the compound can be estimated.

## MATERIALS AND EXPERIMENTAL PROCEDURE

The x-ray diffraction patterns were taken in our high temperature camera which has been described elsewhere.<sup>5</sup> Besides the changes already made,<sup>6</sup> a new collimator was designed, which lowered the exposure time to 1 hour. This was necessary, due to the high evaporation rate of aluminum, even in the presence of 1 atm. of helium. The temperature was measured with a Leeds and Northrup disappearing filament optical pyrometer which had been calibrated against a standard lamp obtained from the National Bureau of Standards. The temperature calibration of the camera was carried out by placing a "black body" made from a piece of tantalum tube, in place of the x-ray specimen. By taking account of the various calibration and correction factors, the uncertainty in the reading of the pyrometer, and the slight temperature variations during the runs, the temperature may be considered accurate to within 20°. Ni-filtered Cu K<sub>1α</sub> radiation, obtained from a Machlett Tube operated at 50 Kv. and 20 Ma., was used.

The Al and  $\text{Al}_2\text{O}_3$  were obtained from the I. T. Baker Chemical Co., and were of "Purified" and "Analyzed" grades, respectively. Rods of  $\frac{1}{32}$ " diameter and  $\frac{1}{4}$ " length were pressed from  $\text{Al}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3 + \text{Al}$  and placed into the camera. After filling with helium, the camera was heated and the x-ray diffraction patterns were taken. For every x-ray determination a new sample was employed.

### EXPERIMENTAL RESULTS

The  $\alpha\text{-Al}_2\text{O}_3$  was found to have the same crystal structure at  $2000^\circ\text{C}$  as at room temperature. Since aluminum is a liquid above  $660^\circ\text{C}$ , it does not contribute any lines to the x-ray diffraction patterns.

Two sets, or series, of experiments were carried out: Set No. 1 corresponded to the composition ratio 4:1 for Al :  $\text{Al}_2\text{O}_3$ , while Set No. 2 corresponded to the ratio 1:1.

The x-ray diffraction patterns obtained from Set No. 1 indicated that at  $1000^\circ\text{C}$  no reaction occurred, while at  $1100^\circ\text{C}$  a new set of lines (corresponding, as we will see later, to  $\text{Al}_2\text{O}$ ), besides those for  $\text{Al}_2\text{O}_3$ , appeared. The diffraction pattern from  $\text{Al}_2\text{O}$  is consistent with a cubic structure having a lattice constant of 4.98 Å. The interplanar distances are given in Table I.

Diffraction patterns obtained from Set No. 2 (Al :  $\text{Al}_2\text{O}_3 = 1:1$ ) show that the Al lines, at room temperature, are much weaker than those from Set No. 1. This is to be expected since the ratio of Al to  $\text{Al}_2\text{O}_3$  is now 1:1 instead of 4:1. At  $1100^\circ\text{C}$  the same new lines (those for  $\text{Al}_2\text{O}$ ) appear as before, but they are much weaker. At  $1500^\circ\text{C}$  another set of lines, belonging, as we will see later, to  $\text{AlO}$ , appear together with the  $\text{Al}_2\text{O}$  lines. At  $1700^\circ\text{C}$ , only the  $\text{AlO}$  lines appear. The  $\text{AlO}$  diffraction pattern leads to a cubic structure with a lattice constant of 5.67 Å. Interplanar distances are given in Table II.

At  $1900^\circ\text{C}$  the whole sample (15 mg) vaporized within one hour, indicating that  $\text{AlO}$  has a high vapor pressure at that temperature.

On every pattern  $\text{Al}_2\text{O}_3$  lines are present. This can be expected to be due to the fact that some Al evaporates during the

TABLE I

X-RAY DIFFRACTION LINES OF  $\text{Al}_2\text{O}_3$  AT  $1100^\circ\text{C}$ 

<u>Intensity</u>	<u><math>\sin^2 \Theta</math></u>	<u><math>d(\text{in } \text{\AA})</math></u>	<u>Indices h, k, l</u>
Strong	0.0729	2.85	1, 1, 1
Medium	0.1157	2.26	2, 1, 0
Medium	0.2107	1.67	3, 0, 0    2, 2, 1
Weak	0.3438	1.31	3, 2, 1

TABLE II

X-RAY DIFFRACTION LINES OF  $\text{AlO}$  AT  $1700^\circ\text{C}$ 

<u>Intensity</u>	<u><math>\sin^2 \Theta</math></u>	<u><math>d(\text{in } \text{\AA})</math></u>	<u>Indices h, k, l</u>
Strong	0.0548	3.28	1, 1, 1
Medium	0.0923	2.52	2, 1, 0
Medium	0.1091	2.33	2, 1, 1
Weak	0.1502	1.98	2, 2, 0
Medium	0.2012	1.71	3, 1, 1



exposures thereby shifting the equilibrium in the two reactions  $4\text{Al} + \text{Al}_2\text{O}_3 \rightleftharpoons 3\text{Al}_2\text{O}$  and  $\text{Al} + \text{Al}_2\text{O}_3 \rightleftharpoons 3\text{AlO}$  to the left. Because of the rapid disproportionation into Al and  $\text{Al}_2\text{O}_3$ , every attempt to obtain diffraction patterns for the two compounds at room temperature by rapidly quenching the samples was unsuccessful.

## DISCUSSION OF RESULTS

The investigation showed the existence of two lower aluminum oxides in the solid phase, each having a cubic structure, the lattice constants being 4.98 and 5.67 Å. The problem now is to decide which is  $\text{Al}_2\text{O}$  and which is AlO. Let us call the compound formed at 1100°C "Compound 1" and the one at 1700°C, "Compound 2."

All diffraction pictures were obtained using the same x-ray intensity and exposure time. The  $\text{Al}_2\text{O}_3$  pattern is present on every picture with about the same intensity. Thus the relative intensity of the new diffraction patterns gives information as to how much Al is needed (compared to  $\text{Al}_2\text{O}_3$ ) in the formation of the compounds. The ratio Al: $\text{Al}_2\text{O}_3$  was 4:1 in the first set, and 1:1 in the second set. A visual comparison of the intensities of the different diffraction patterns shows that the intensity of the new diffraction pattern in Set No. 2 at 1700°C is much stronger than that for the new diffraction pattern in this same set at 1100°C, and that the intensity of the new pattern in this set at 1700°C is about equal to that in Set No. 1 at 1100°C. For the same amount of Al, less of Compound 1 is formed than of Compound 2. Similarly, to form the same amount of material, more Al is needed for Compound 1 than for Compound 2. It therefore follows that Compound 1 (at 1100°C) is richer in Al than is Compound 2. Thus Compound 1 is  $\text{Al}_2\text{O}$  while Compound 2 is AlO, as was assumed during the description of the patterns.

From the diffraction patterns obtained, the stability against disproportionation into Al and  $\text{Al}_2\text{O}_3$  of the lower oxides in solid form can be deduced. Below 1000°C only liquid Al and  $\text{Al}_2\text{O}_3$  are stable.  $\text{Al}_2\text{O}$  is stable between 1050° and 1600°C, and AlO is stable above 1500°C.

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